LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Reference System for Cryogenic Coating Noise Measurements
SURF Project 2016

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1 Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is a large scale project aimed at detection and study of Gravitational Waves. The current Advanced LIGO Detectors are some of the most sophisticated and sensitive sensors for length fluctuations ever made. These interferometers measure strain in their arms in the order of a few 10^{-24} in the frequency range of 10Hz to a few kHz. Instruments that aim at such delicate measurements are inherently prone to a wide range of noises.

One such source of noise is the Brownian noise in the coating of the test masses which arises from the coupling between macroscopic degrees of freedom and the thermal energy in the mirrors according to the fluctuation dissipation theorem[1]. While Brownian noise also emerges in the substrates and suspensions, the coating contribution presents a severe limitation to the achievable instrument performance between 40 and 200 Hz[2].

It is thus important to improve the mirror coatings and reduce the effects of this noise. A possible approach in doing so is cryogenically cooling the test masses so as to lower the thermal energy in the test mass, in turn lowering the Brownian noise. Due to the fact that fused silica is not well-behaved towards lower temperatures, silicon is an attractive alternative for its mechanical properties and thermal characteristics[3].

During this summer, I will work on a pre-existing work bench designed to measure the coating thermal noise in sample mirrors at cryogenic temperatures. The bench consists of two nominally identical optical cavities with independent lasers locked to them. Using this setup for a differential measurement of the resonance frequency fluctuations in the two cavities, one can directly measure the coating thermal noise that dominates these cavities by design.

The next generation of test cavities will only be several centimeters long, which enhances the conversion from length to frequency fluctuations. It however also carries a risk of too high beat frequencies for the low-noise photo detectors used in the experiment. The measurement becomes simpler if each of these two setups is compared with a third reference setup, which features lower intrinsic noise in its cavity. I will be setting up this reference bench and incorporate it into the existing work bench.

2 Objective

The goal of my work for the summer is to set up an optical frequency reference to aid the characterization of coating noise in cryogenically cooled silicon cavity optics.

Unlike LIGO in its current state, the experiment uses silicon optics because fused silica is not well-suited as a substrate material at cryogenic temperatures due to increased mechanical loss and low thermal conductivity. This in turn requires that we transition to 1550nm lasers, because silicon is too absorptive at 1064nm.

Due to manufacturing tolerances, the relative location of the resonances in the test cavities are somewhat uncertain. Since they are very short by design, they have large free spectral ranges in the GHz range, and upon differential measurement, in case the locking frequencies are far apart, the beating output will be too fast to be detectable by the photo detector. As a contingency plan for beat measurements and a diagnostic tool for debugging the original test bench, the proposed modification of the setup is the addition of an external reference system.

Thus, I will be setting up the reference bench, which features an independent laser and a third optical cavity. The silica reference cavity exists from the early stages of the cryogenic test bench. This cavity will be placed inside a separate vacuum tank on a separate optical table. Feedback controls, which need to be optimized, will keep the laser system on resonance with the cavity. The stabilized transmitted light will be guided to the test bench with an optical fiber.

3 Approach

In the early stages of the experiment a fused silica cavity for initial testing of the laser feedback was assembled, shown in Figure 1. It is much longer than the next generation of test cavities and supports larger beams, which dilutes the impact of coating noise. The cavity is therefore intrinsically less noisy, and can be used as a frequency reference for the coating noise induced frequency fluctuations in the test cavities. Similar cavities have been used in the past for room temperature measurements of coating thermal noise[4].

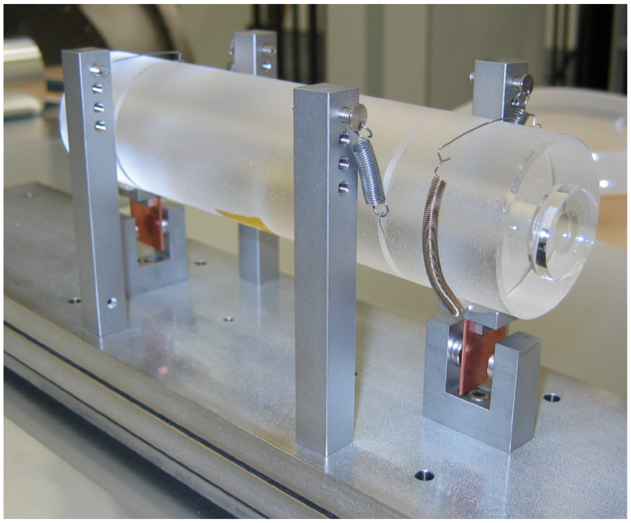


Figure 1: The Fused-Silica Reference Cavity.

To build this reference system, I will characterize the additional fibre-coupled laser system (electronic response, spatial profile) and find a lens solution to match the spatial mode supported by the cavity. With a laser system probing the reference cavity I will then determine its optical properties and use the measurements to establish and optimize the feedback to the laser frequency using the Pound-Drever Hall[5] technique. This locks the laser frequency to the cavity resonance and causes the majority of the laser light to be transmitted in the cavitys fundamental mode.

I will then direct the output of this setup to the work-bench, which is located on a different table, via an optical fibre. On the test bench, I will modify the existing setup such that the beams transmitted by either test cavity are additionally interfered with the stabilized reference laser, which enables the differential frequency noise readings. Figure 2 shows the arrangement of the existing bench and the proposed reference bench.

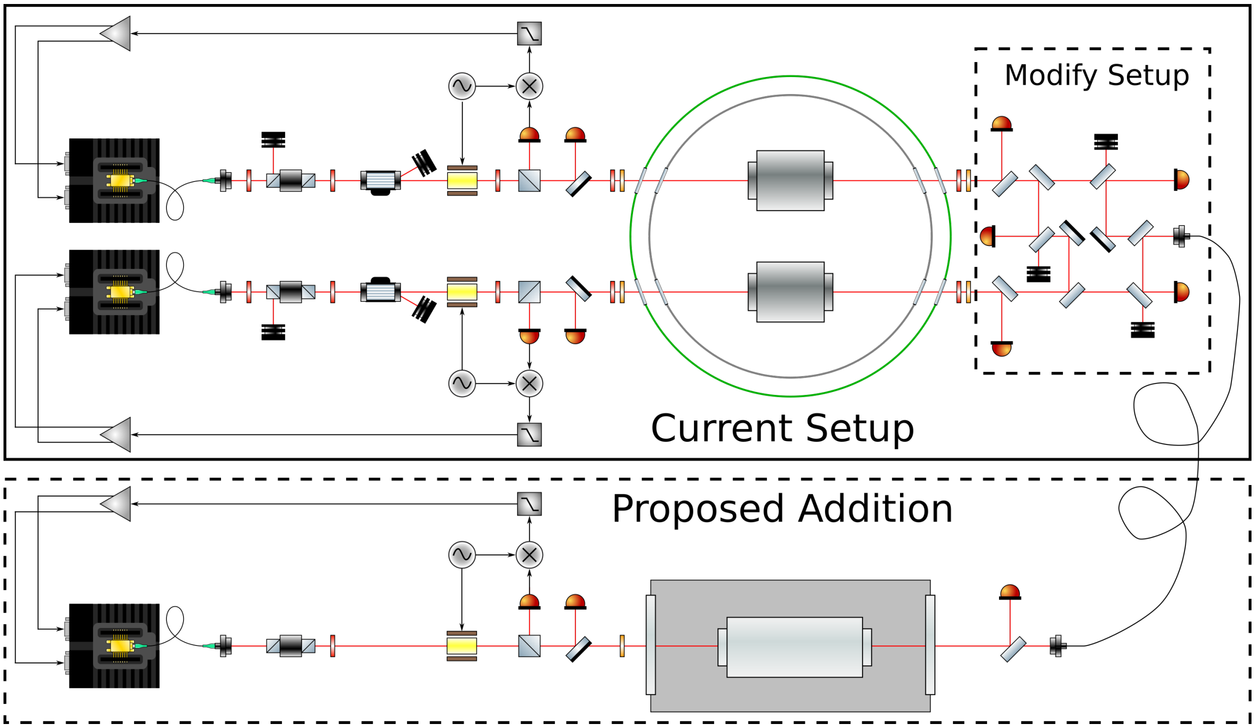


Figure 2: Diagram Showing the Final Setup.

There are a few different methods to obtain these readings and assess the test cavity noise floor. With a well-behaved reference system one can take individual measurements of the test cavities, which requires the reference bench to be locked in separately at appropriate frequencies and therefore does not provide a coherent measurement between the test cavities. More complex, coherent methods exist which involve sideband modulation and do not require locking the reference multiple times. Certain combinations of the data streams can potentially cancel the residual noise output of the reference setup, only measuring the noise from the test optics. The conclusion to my work will be to explore the applicability of some of these extraction techniques.

Upon completion of my tasks, the Cryolab at Caltech will have a valuable diagnostic instrument for LIGO optics which streamlines coating noise measurements and can help identifying problems in the setup.

4 Program Schedule

Week	Task Focus
1	Becoming familiar with laser operation and beam diagnostics
2	Mode measurements and matching with lens solutions
3	Setting up the front optics guiding the beam into the cavity
4	Cavity characterization and initial feedback setup
5	Place cavity in vacuum tank, evacuate; feedback optimization
6	Back optics setup and fiber-coupling of transmitted light
7	Test bench modifications
8	Beat note setup with primary lasers; contrast optimization
9	Measure frequency noise with different electronic demodulation techniques
10	Application of advanced high frequency demodulation techniques

5 Progress Report

5.1 Week : 1

I spent the first week familiarizing myself with the lab and the components I'll be using, like network analyzers and oscilloscopes. I learned the process of setting up phase locked loops and delay lines in preparation for the upcoming tasks. The optical tables in the cryo lab needed to be swapped and hence we prepped the optical tables for the swap, labeled all the wires, and cleaned up the lab.

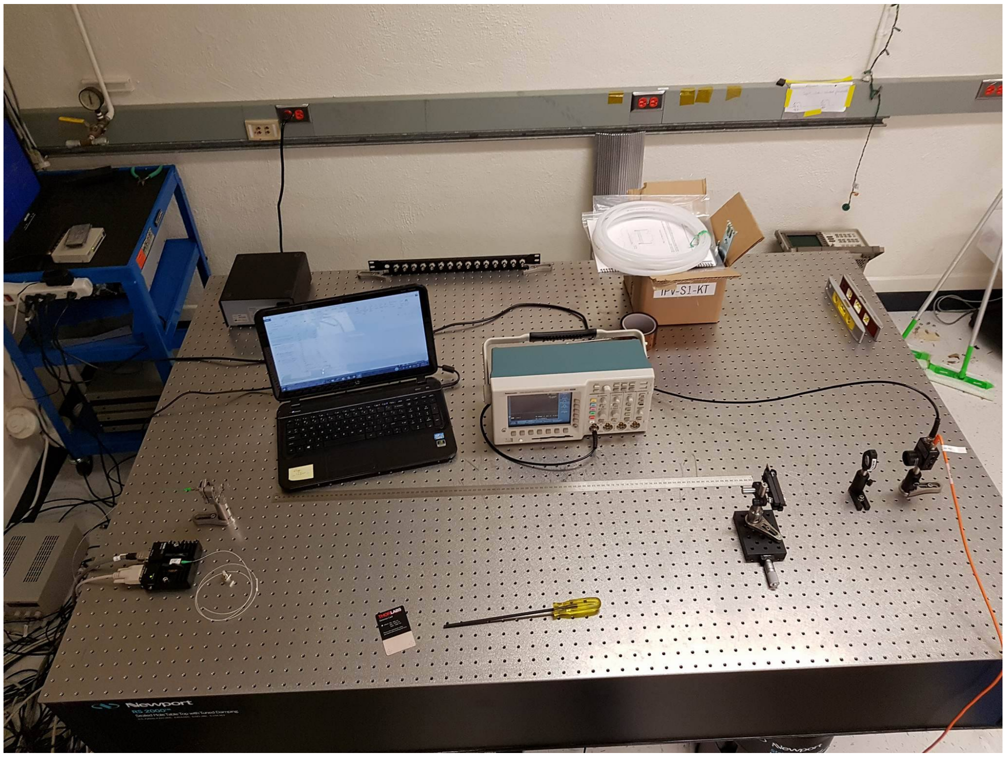
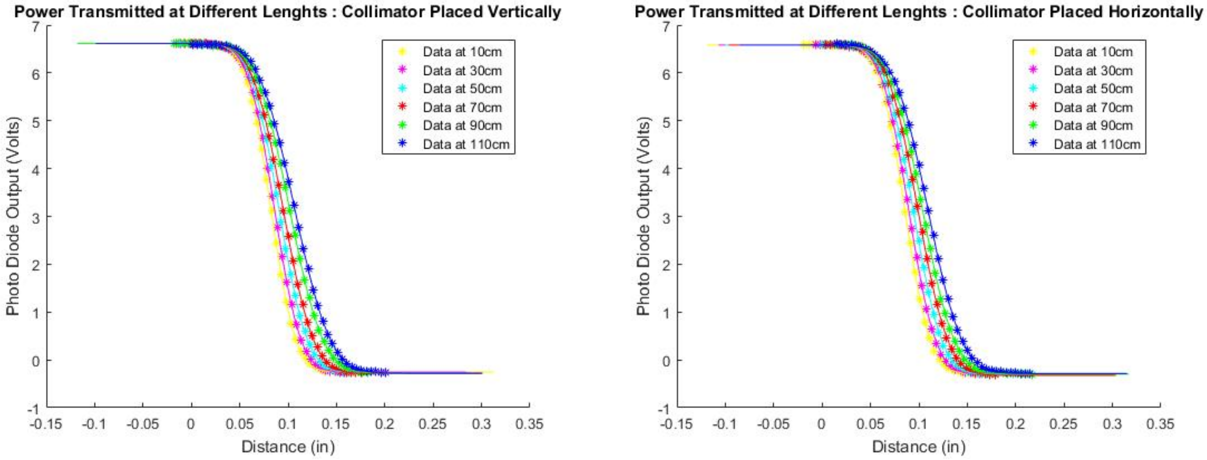


Figure 3: Setup For Finding Beam Parameters.

I tested the fiber-coupled laser I will be using for the reference cavity and mapped out its beam profile. I used a razor-edge as an obstruction to the laser beam and mapped out the photodiode power output for various depth of the blade at various distances from the collimator, as shown in Figure 3. The razor edge eclipses the beam at different distances, alloying only a part of the beam to propagate, resulting in the observed integrated intensity curve. This curve is characteristic of the beam spot size at that location. I repeated this procedure at different distances from the collimator and got the beam spot size at different distances, then repeated the whole process again with the collimator rotated by 90^o. I used Matlab to fit all the sets of data into the theoretical equations and got the beam width and the location of the width by extending the plot of beam spot size vs distance, as shown in Figure 5. The photodiode output (integrated intensity curve) is shown in Figure 4.



(a) Collimator Placed Vertically

(b) Collimator Placed Horizontally

Figure 4: Photo-Diode Output at Various Distances From Collimator

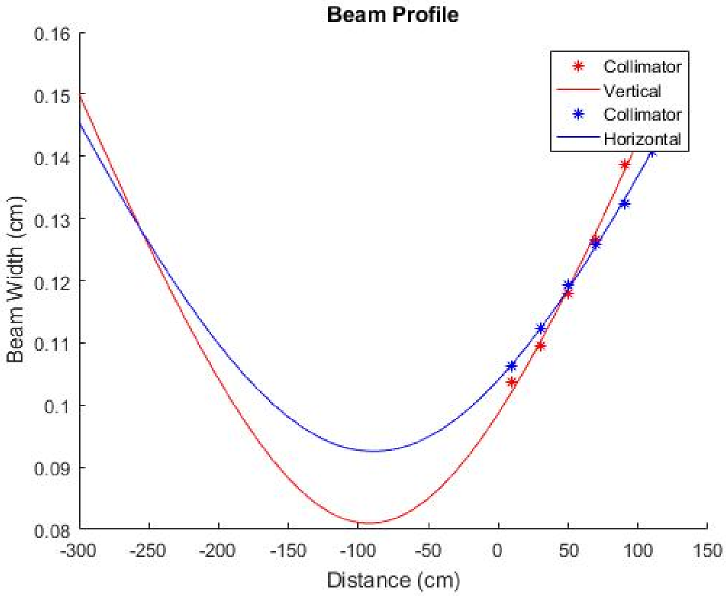


Figure 5: Beam Spot-Size Along Beam Axis.

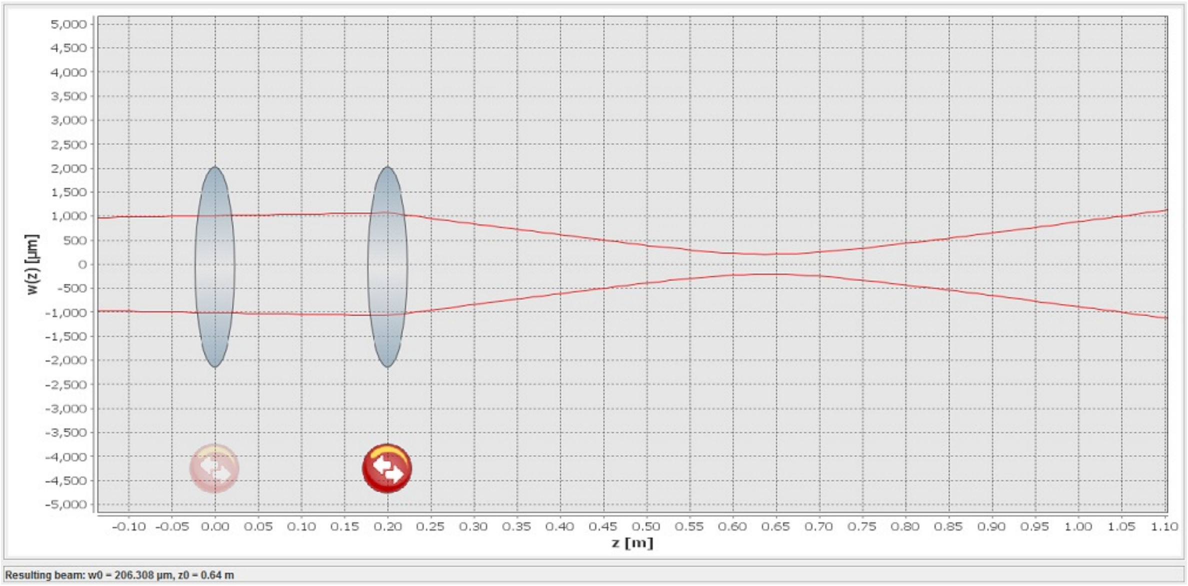
The beam width (with the collimator placed vertically) was found out to be 0.81mm at a distance of 92.53cm behind the collimator. The beam width (with the collimator placed horizontally) was found out to be 0.925mm at a distance of 89.23cm behind the collimator. I took the average of the two to approximate the beam waist and location for the mode matching calculations.

5.2 Week : 2

I read up on the Pound-Drever-Hall [5] laser locking technique, beam mode matching and optical cavities [6]. I also worked out the cavity characterizations, which is required for the mode matching and lens solutions. The reference cavity I'll be using is 8 inches or 20.23cm long and has one flat mirror, and one concave mirror with a radius of curvature (ROC) of 50cm at the two ends. The mode calculations tell that a beam with a waist of 0.3482mm, which is located at the position of the plane mirror, is supported by the cavity. After the optical tables were swapped, I grabbed the data for mapping the beam profile of the remaining two lasers to be used on the test bench using the above mentioned technique.

5.3 Week : 3

During the last week I swapped some the components from the two tables. The cryostat was shifted from the old table onto the new one, and I started by interfering the two test lasers with each other and observed the beat note on an oscilloscope. Beat note is the interference pattern between the two lasers which is observable when the frequencies of the two lasers are close enough (it is otherwise too fast to be picked up by an oscilloscope). Any frequency noise in the beat note is due to the frequency noise between the two lasers, thus its measure tells us how noisy the lasers are. I then attempted to lock the beat note to a signal generator using a phase lock loop to measure the frequency noise of the beat note, but was unsuccessful. The reasons might be that the signal generator isn't fast enough to lock on to the rapidly changing beat note. I have to look into this in a bit more depth. Simultaneously, I have worked out a lens solution for the reference bench, as shown in Figure 6. The Electro-Optic Phase Modulator is placed at a distance of 65cm from the collimator where the beam is thinnest. This makes sure the beam passes freely through the 2mm free diameter of the Electro-Optic Phase Modulator. The first lens is the collimator and the second lens used is of focal length 400mm and is placed at a distance of 20cm from the collimator. I started assembling the components on the other table. The assembly till the Electro-Optic Phase Modulator was done. The rest required the position of the reference cavity, which I needed to predict.

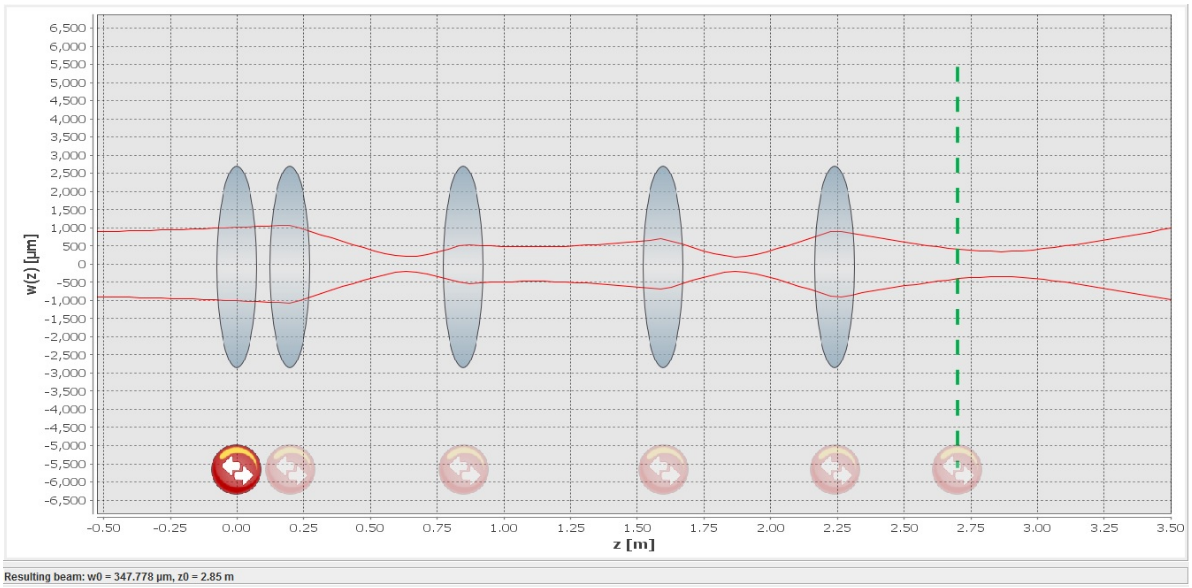


Resulting beam: w0 = 206.308 μm, z0 = 0.64 m

Figure 6: Screen-shot from the mode matching software.

5.4 Week : 4

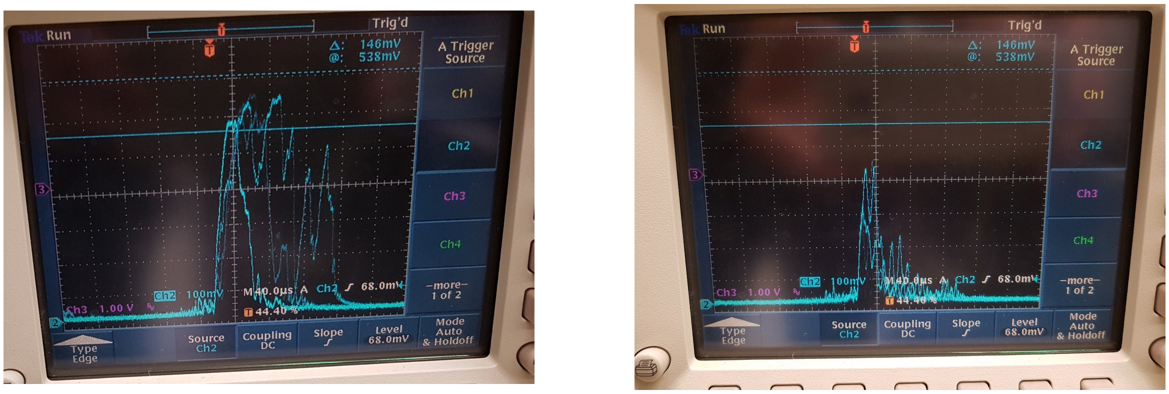
I measured the dimensions of the cylindrical vacuum chamber. Then I did the mode matching to obtain the required beam waist at the predicted location, which is shown in Figure 7. The initial beam waist is 867.5μm located at -90.88cm and the final beam waist is 347.8μm at 285cm in front of the collimator, which is at the origin. The focal lengths of the lenses from left to right are 400mm, 200mm, 225mm, and 250mm. The locations of the lenses from left to right are 20cm, 85cm, 160cm and 224cm. I then placed the lenses in position, measured the mode and adjusted the lenses again in the order of 1 cm to get a closer mode of 353μm. After fixing the mode setup I added the wave-plates, polarizing beam splitter and the EOM.



Resulting beam: w0 = 347.778 μm, z0 = 2.85 m

Figure 7: Lens positions for Mode Matching.

I placed the cavity according to the position calculated and scanned the laser frequency using a ramp current feedback across a range of 2 V_{p-p} to observe the transmitted 00 mode using a CCD camera and a photodiode. I added a Faraday isolator, which is an optical diode, to the setup to prevent the reflected light from destabilizing the laser and that seemed to help with the laser noise. After optimizing the beam alignment, I got a transmission through the cavity, as shown in Figure 8. I then determined the visibility of the setup, which is the fraction of the incident light that resonates in the fundamental mode, by manually scanning the laser over one free spectral range and noting the power transmitted for different modes transmitted by the cavity. Adding all the transmitted powers and dividing by the total power of the laser, I found the visibility to be 85%.



(a) Before adding faraday isolator

(b) After adding faraday isolator

Figure 8: Photodiode output of transmitted 00 mode.

5.5 Week : 5

I started working on the EOM modulation signal. A typical choice for a PDH setup is a modulation index of 0.3. As per the datasheet of the EOM, the half wave voltage for light of wavelength 1550nm is around 330 Volts. Thus to get a modulation of 0.3 radians, we needed a signal of 34dBm. I used a low noise amplifier of 36dB, which had a max input limit. So I added a 16dB attenuator to avoid overdriving the amplifier. I had to add a resonant circuit of 6dB to reach the desired voltage. I modulated the light at the resonant frequency and observed the sidebands on the photodiode by sweeping the laser with a ramp signal. With these modulated sidebands, I was able to determine the tuning coefficient of the laser to be 11.32MHz/V. After that I working on the delay line (which is essentially a long cable to delay the phase) for the feedback loop to correct for the phase difference in the two paths and observed the error signal. I got a better error signal by varying the cable length to best compensate for the phase difference and finally adjust the modulating frequency, which is shown in Figure 9.

I had to swap the reference laser with one of the primary lasers as the former stopped working. With the cavity in place and the error signal set up, I started trying to lock the laser onto the cavity using a servo amplifier. The free spectral range of the cavity and finesse of the cavity was known, using which I estimated the pole location of the cavity to be greater than 100kHz and set the PI controller as a pure integrator (as the pole would be far from

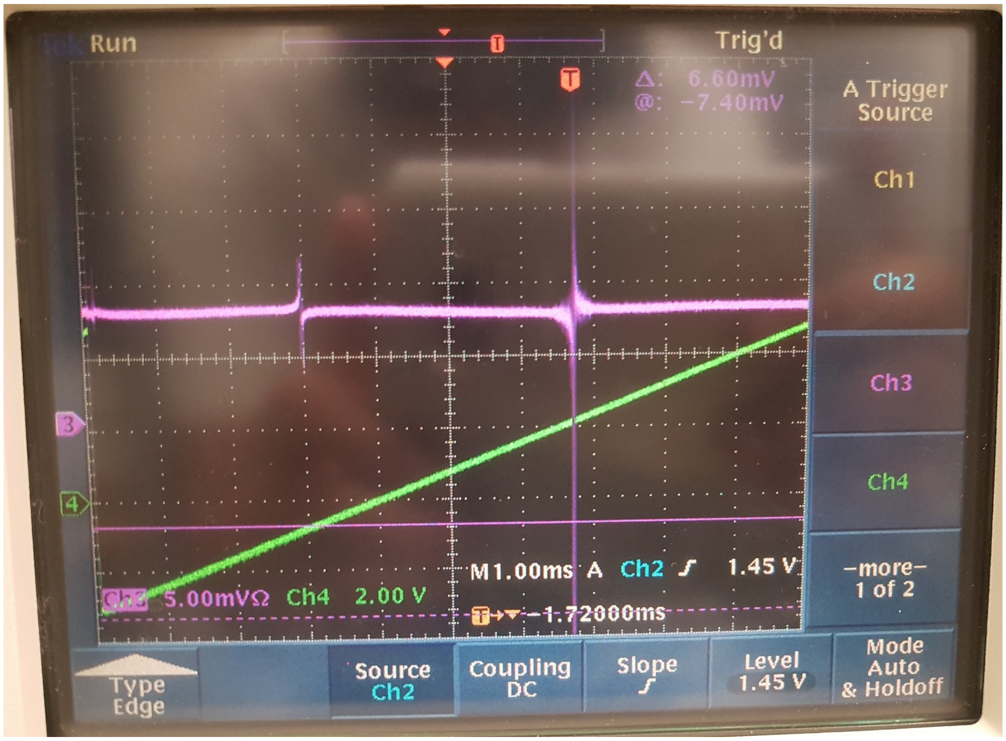


Figure 9: Error signal depicting Carrier Band and one Side Band.

the operating range of our feedback system) with 30dB low frequency cutoff and a gain of around 5. Then by slowly modifying the parameters I achieved a solid lock of the 00 mode. The transmitted 00 mode is shown in Figure 10.

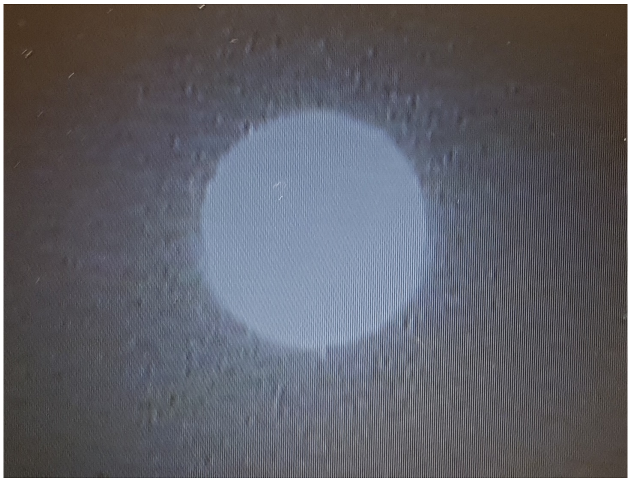


Figure 10: Beam spot as seen on the CCD camera

5.6 Week : 6

To improve the transmission, I measured the laser mode at the cavity again, as the swap of the lasers might have changed the incident mode. I found that the beam waist remained unchanged but the waist location had shifted towards the source by about 3cm. I reposition the cavity, spend some time getting better settings for the servo amplifier and recovered the previous visibility. The dynamic range of the current frequency feedback is too small and hence the laser is unable to remain locked to the cavity for extended periods of time. A possible solution to this is to use a second hierarchical feedback loop for the laser temperature which will stabilize the larger but slower variations in the laser frequency, like due to changes in the ambient temperature. This way the current control will take care of the faster actuations much more effectively and remain in its operating range. I also obtained the current vs power characteristics of the laser, shown in Figure 11. Note that this characteristic depends on the temperature operating point.

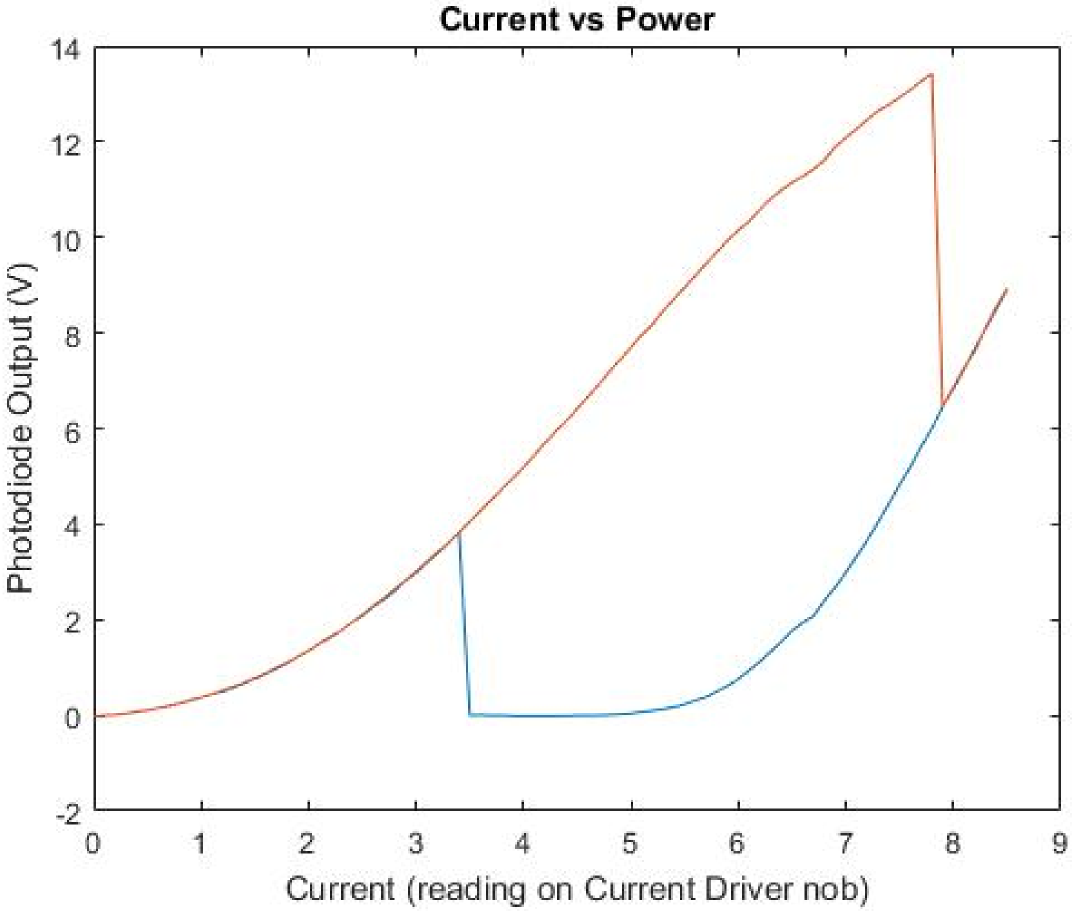


Figure 11: Current VS Power hysteresis of the laser.

5.7 Week : 7

Now that the laser had a decent lock on the cavity, I measured the feedback loop transfer function using a network analyzer, which is shown in Figure 12

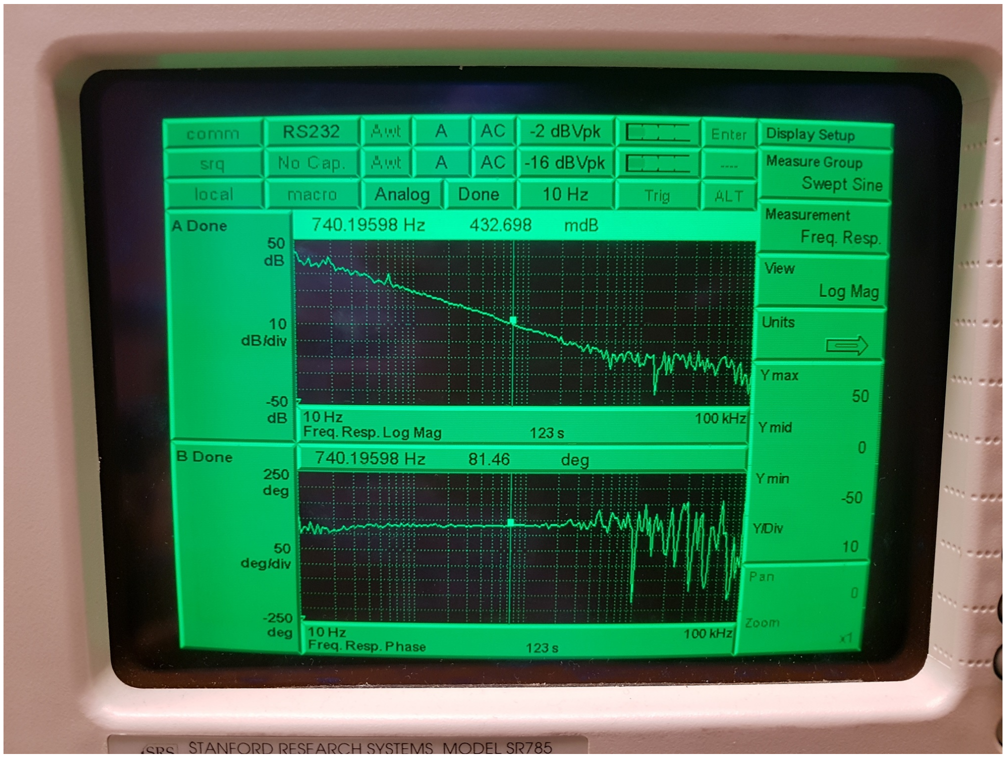
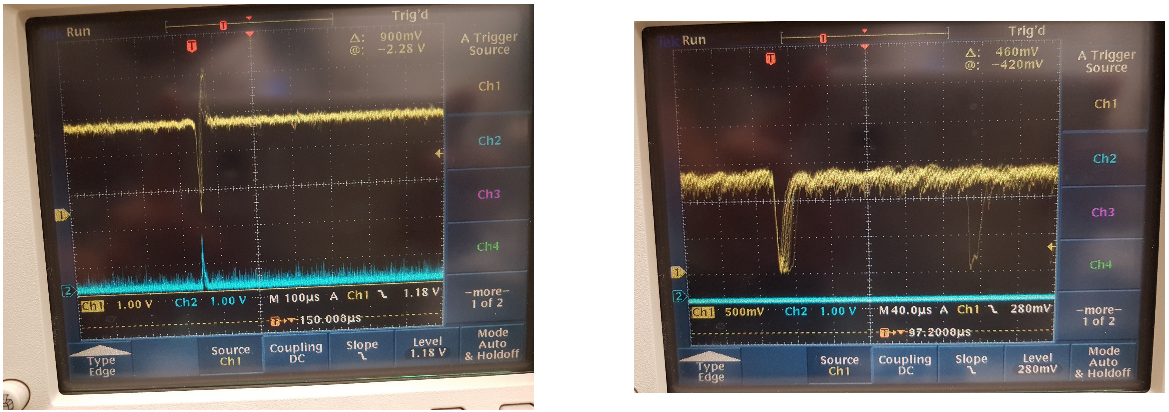


Figure 12: Transfer Function and Phase.

I tried to measure the cavity pole so as to design a better feedback loop for the cavity. I added an AOM (Acousto-Optic Modulator) and a beam dump for it to the reference bench to modulate the light intensity. The AOM was placed immediately after the EOM (where the beam spot size was relatively small) and the deflected light was blocked off by a beam dump. A direct measurement of the cavity transfer function would be polluted by the transfer functions of various electronic components. I planned to use the modulating chirp signal from the network analyzer to drive the AOM driver. This way, I could find the transmitted light intensity transfer function for the setup. By doing this twice, once with the cavity in place and then with it removed, I would get the transfer functions with and without the cavity. Then by dividing these two I would get the frequency response of the cavity, and finally the cavity pole from it.

However, despite well-in-range signal levels, the network analyzer was indicating an overload on the transmitted light input. Upon looking at the transmitted light intensity from the photodetector on an oscilloscope, it seemed that the signal had an occasional glitch which might have been the cause of the overload. The glitch had no clear periodicity but had a distinct shape. It was unaffected by the gain of the servo amplifier which might indicate that it originated in the current driver. Changing the driving current of the laser seemed to change the shape of the glitch too. At a higher driving current, the glitch had an overshoot, but at a lower driving current, the overshoot was absent and the shape looked as if it was damped, as shown in Figure 13. As the network analyzer failed to provide the transfer function with the cavity in place, I removed the cavity to obtain the transfer function without the cavity. I might have to do the transfer function calculation with the cavity manually by changing the frequency in steps and plotting the gain against it.



(a) With laser at a higher operating point

(b) With laser at a lower operating point

Figure 13: Glitch observed in transmitted light

5.8 Future Goals

The next task would be to move the vacuum tank in place and set up the cavity inside it. Then make fine adjustments to get the position of the cavity right. I will then any changes required to the feedback setup. Then the vacuum tank can be evacuated and final touches can be made to the feedback system.

I will simultaneously be working on recreating the test bench on the new optical table and making modifications to it so as to incorporate the reference cavity output with the primary lasers. Then the output of the reference cavity will be fiber-coupled and guided into the test bench to be set up so as to observe the beat note between the reference laser and primary laser.

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